Turbulence Off the Coast of Oregon:
A Large-Eddy Simulation Study

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LONG-TERM GOALS

Our long-range research goal is to improve understanding of small-scale mixing processes in the coastal ocean environment and to incorporate the effects of these processes in coastal ocean models. We will increase the accuracy of coastal mesoscale prediction models by adding physically-based approximations to one-dimensional mixing parameterizations.

OBJECTIVES

Recent studies of the open ocean upper boundary layer using large-eddy simulation (LES) methods have demonstrated the value of these models in describing turbulent processes in the ocean. We are now at a point where LES can be applied to a broader range of problems that include the coastal surface and benthic boundary layers. Our objectives in this work are to determine the accuracy of LES models in coastal flow scenarios, examine the role of turbulent mixing in defining boundary layer structure, and apply observations and LES results to understand and improve commonly applied mixing parameterizations (e.g. Mellor and Yamada 2.5 model and the K profile parameterization). Specific questions we will address include:

- Are Langmuir cells important in inner- and mid-shelf surface layers?
- How do mixing properties (dissipation rates, buoyancy fluxes, surface and bottom boundary layer stresses) vary from one location to another?
- Do the M-Y and KPP mixing schemes predict local turbulent processes in the Oregon shelf?
- What is the role of small-scale bathymetry variations (vertical scale ~O(1 m), horizontal scale ~O(10 m)), especially in the inner shelf?
- What are the fundamental differences in mixing statistics of M-Y, KPP, LES, and microstructure measurements?

APPROACH

The central hypothesis of the proposed effort is that improvements in existing parameterizations of turbulent processes require a physical basis and that this basis may be gained through analyses of LES

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results and turbulence observations. To test this hypothesis, we propose to predict the three-dimensional physical structure of mixing in the coastal environment by conducting a series of experiments using an LES model driven by mesoscale forcing. These model experiments will focus on three main topics:

- Validation of the model using measurements of turbulence structure and evolution.
- Comparison of LES derived turbulence parameters, such as turbulent kinetic energy budget terms, with parameterizations, specifically the M-Y model and KPP.
- Detailed analysis of turbulence in the coastal environment and modification of parameterizations to include new physical insight.

We apply the Ocean Large Eddy Model (OLEM) (Skyllingstad et al. 1999), which is designed to simulate flow encompassing several hundred meters in each horizontal direction and tens of meters in the vertical. The domain is large enough to accommodate the dominant energy containing motions, e.g. Langmuir Circulation, convective rolls, and Kelvin-Helmholtz shear instabilities. A domain size of approximately 256 x 256 grid points in the horizontal direction and 128 points in the vertical will be used with a resolution of ~0.5 m. Longer term boundary layer growth will be simulated using 1.0 m resolution over a domain of 256x256x64 grid points.

Experiments will be initialized using observed profiles of state variables and by using output from the POM coastal model, which is being used in the NOPP program. Mean currents will be maintained during the POM comparison simulations by imposing a horizontally constant large-scale pressure gradient representing the local balance of forces from the POM model. Case studies will be selected based on the synoptic scale situation (i.e. upwelling or downwelling) and the availability of turbulence observations. Our plan is to pick cases for moderate upwelling scenarios when southward, alongshore currents are relatively strong.

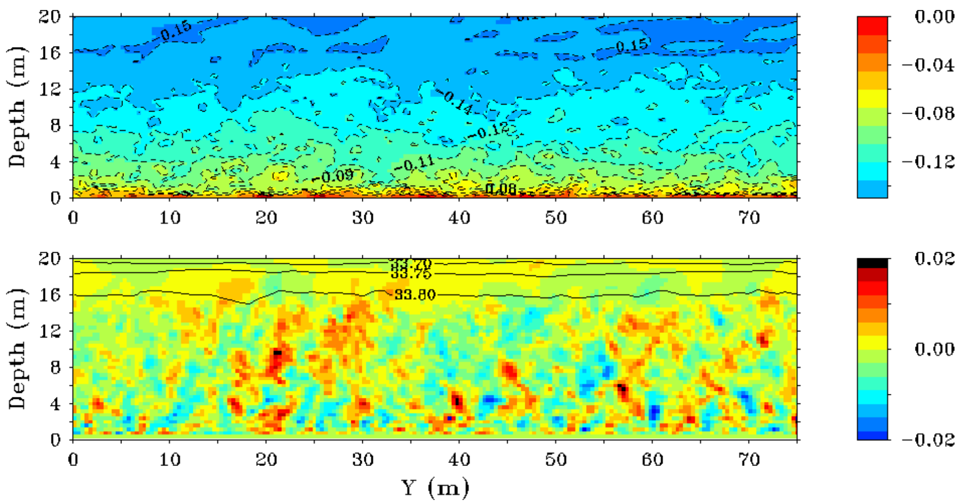
WORK COMPLETED

Both LES and POM Experiments were started concentrating on the bottom boundary layer structure off the Oregon coast. For the LES cases, a typical flow scenario for coastal upwelling was used to examine the turbulent behavior of the bottom boundary layer. POM simulations focused on a similar coastal domain and tested three mixing parameterizations: KPP, Mellor and Yamada, and K-epsilon. Results from these experiments will be reported at the Fall 2000 AGU meeting.

RESULTS

Our focus during the first year of research has centered on the bottom boundary layer structure during upwelling events. We present preliminary results starting with the LES model.

Observations taken during the NOPP 1999 cruise showed that the bottom boundary layer (BBL) is typically O(10 m) deep and is physically separated from the surface boundary layer. The BBL is thought to behave like a wall boundary layer with the southward currents forced during upwelling events providing a source of bottom shear stress. Our first simulations concentrate on a typical bottom boundary layer structure having a ~10 m bottom layer of uniform temperature and salinity with a



1. Vertical cross section showing vertical velocity and salinity (bottom) and meridional velocity (top). This snapshot from the LES model is taken after 5 hours of spin up.

gradual decrease in salinity and increase in temperature above 10 m. Resolution in this experiment is set to 0.4 m with a domain size of ~100 m in each horizontal direction and ~25.5 m in the vertical.

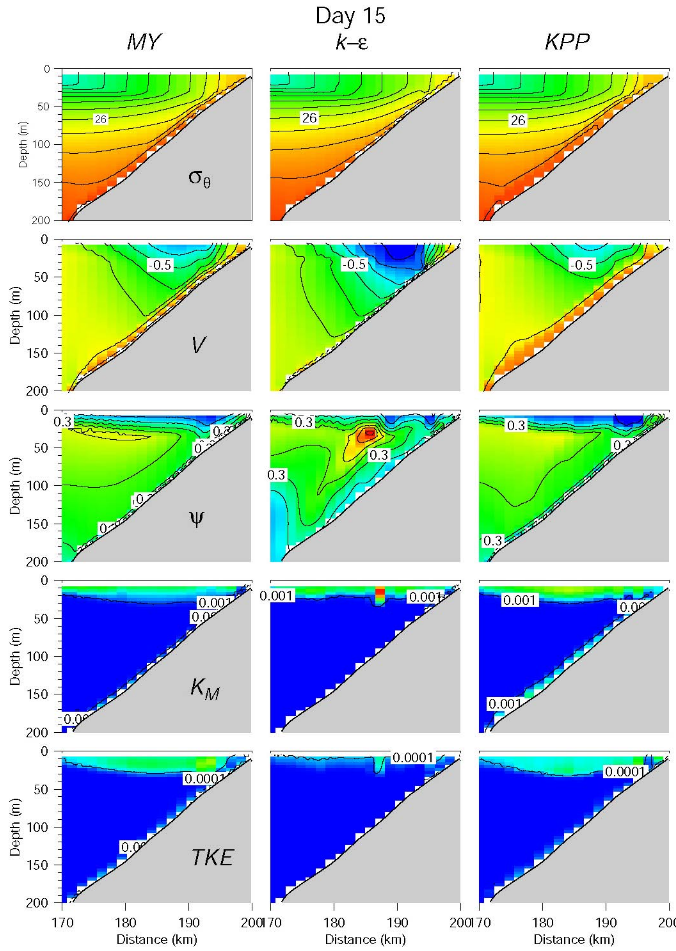
Cross section plots of the modeled vertical velocity, salinity, and meridional current show a typical snapshot of the turbulent BBL structure (Fig. 1). Overall, the structure is rather random, but with consistent scales dependent on the distance from the bottom. For example, turbulent eddies shown in the vertical velocity tend to scale with depth, increasing in size as one moves from the bottom upward to the stable overlying water. The shear structure also shows a consistent pattern with depth, namely higher shear near the bottom that decreases moving upward.

The structure shown in Fig. 1 is consistent with wall-layer behavior that predicts a log profile for shear, and log-linear profiles of turbulence dissipation rate.

Results from the LES demonstrate that using a wall-layer or Monin-Obukhov similarity theory approach for the ocean BBL is consistent. However, we note that observations of turbulence dissipation rates also indicate a high degree of variability that may not be explained by typical variations in BBL flow. These variations are likely a result of bottom roughness elements that extend well into the BBL (~1-5 m size obstructions). For example, the NOPP cross sections show a consistent increase in turbulence dissipation in regions where the bathymetry is changing more rapidly, which may indicate a rock outcrop or other roughness feature. In our upcoming work, we plan to investigate the effects of resolved roughness elements (in addition to aerodynamic roughness) and determine if similarity theory can be adapted to account for these features.

Parameterizations

The sensitivity of model-produced time-dependent upwelling circulation on the Oregon/California shelf to turbulent closure schemes has been examined using the Blumberg-Mellor finite difference, hydrostatic primitive equation model (POM). The 2.5 level Mellor-Yamada (MY) closure (Mellor and



1: Fields of the density σ_θ (kg/m^3) the alongshore velocity V (m/s), the streamfunction for the across-shelf flow ψ (m^2/s), the vertical eddy diffusivity K_M (m^2/s), and turbulent kinetic energy TKE (m^2/s^2) at day 15 for three different mixing schemes, MY, k-ε, and KPP. The contour intervals are $\Delta\sigma_\theta = 0.1$ kg/m^3, $\Delta V = 0.1$ m/s $\Delta\psi = 0.1$ m^2/s. K_M varies from 0 to 2x10^{-2} m^2/s and TKE varies from 0 to 5x10^{-4} m^2/s^2.

Yamada, 1982), *k-ε* closure (Buchard et al., 1998; Rodi, 1987), K-Profile Parameterization (KPP) closure (Large et al., 1994) have been used to study the structure and strength of vertical mixing, which in turn is used to examine the sensitivity of the time-dependent upwelling circulation to a given turbulent sub-model. We have conducted both two-dimensional (2-D) and three-dimensional (3-D) POM simulations. The summary given below shows 2-D meso-scale flow field for the three mixing schemes. Some of the work presented here is also a continuation of NOPP mixing studies (collaboration with John Allen and his co-workers). The 2-D model domain extends about 200 km offshore with horizontal resolution of about 0.25 km. The model has 60 levels with topography representing shelf and slopes off Newport, Oregon. The model generated mixing structure is examined for both forcing and relaxation of the winds. The model is initialized with horizontally homogeneous density and a constant upwelling favorable wind of about 0.05 N/m^2.

The effects of the different mixing parameterizations for the vertical eddy viscosity (K_M) and eddy diffusivity (K_H) are shown in Fig. 3 for MY, *k-ε*, and KPP sub-models. In the KPP experiment, the

density field is adjusted at each time step to avoid unstable stratification. For the KPP case, TKE is computed form the MY-TKE equation using mixing coefficients of KPP.

The major differences found in these comparisons are in the representation of the upwelling frontal structure, σ_θ, V, and ψ fields. The *k-ε* scheme produces the weakest mixing, shallowest mixed layers, strongest alongshore velocity, and a more complex offshore circulation compared to MY and KPP schemes. The day 15 ψ field for *k-ε* mixing show a circulation cell on the offshore side of the coastal jet, and these spatial oscillations increase especially for times greater than about 20 days. The KPP scheme generates a circulation cell in the inner shelf (by the inshore side of the coastal jet). As shown in Fig. 3, the bottom boundary layer is thicker and mixing is stronger in the KPP case compared to *k-ε* and MY.

We are currently implementing a *k-ε* closure scheme in the 3-D version of POM with realistic west coast topography representing the region of the Coastal Ocean Dynamics Experiment (CODE). Comparison of MY, KPP, and *k-ε* closure schemes for upwelling favorable winds will be discussed in the upcoming Fall AGU meeting.

IMPACT/APPLICATIONS

Much of the work performed here will directly impact the accuracy of coastal prediction models. In most coastal models, the bottom boundary layer is crudely represented with uniform roughness and no boundary layer model. Our work will provide a more solid basis for simulating the effects of bottom roughness variations and interaction with the coastal current structure.

TRANSITIONS

Improvements in the turbulence parameterization models will be incorporated into general purpose versions of POM and made available to the oceanographic community.

RELATED PROJECTS

This work complements efforts in the COAST and Oregon NOPP programs. Both of these projects utilize coastal models that will benefit from improved mixing parameterizations.

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